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Fabrication and Operation of Polyimide Bimorph Actuators for a Ciliary Motion System

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Abstract—In order to extract macroscopic mechanical work out of microelectromechanical systems, we have proposed the concept of distributed micromotion systems (DMMS). The key idea of DMMS is to coordinate simple motions of many microactuators in order to perform a task. Design, fabrication, and operation of a type of DMMS, called a ciliary motion system, are presented. A bimorph thermal actuator using two types of polyimides with different thermal expansion coefficients and a metallic microheater in between them was fabricated. The cantilever-shaped actuator curled up from the substrate owing to the residual stress in polyimides which built up during the cooling process after they were cured at 350°C. It flattened and moved downward by flowing current in the heater. The dimensions of the cantilever were 500 μm in length, 100 μm in width, and 6 μm in thickness. The tip of the cantilever moved 150 μm in the direction vertical to the substrate and 80 μm in the horizontal direction; these were the maximum displacements obtained with 33 mW dissipated in the heater. The cut-off frequency was 10 Hz. On a 1-cm-square substrate, 512 cantilevers were fabricated to form an array. Two sets of cantilevers were placed opposing to each other. We operated them in coordination to mimic the motion and function of cilia and carried a small piece of a silicon wafer (2.4 mg) at 27–500 μm/s with 4-mW input power to each actuator.

I. Introduction

THIS paper deals with the fabrication and operation of microactuator arrays for a type of distributed micromotion systems (DMMS). We proposed the concept of DMMS with many smart modules [1] to make best use of the advantage and to overcome the limitation of microelectromechanical systems (MEMS) which have moving parts of micrometers in size. Unlike conventional machines in which the three-dimensional structure, assembled in various shapes, is tightly associated with its function, the limitation of the typical IC-based fabrication process for MEMS only allows us to make planar structures [2], [3] and micromotors [4], [5] or a projected image of 2-dimensional mask patterns in deep resist [6], [7]. Therefore it is difficult to realize various functions only by changing the shape of the machine. However if we utilize the following features of MEMS, the problem can be solved:

1) Many structures can be obtained simultaneously by preassembly and batch process.

2) The integration with electronic circuits and sensors is possible with the IC-compatible micromachining technology.

We can have many complicated modules in IC-based MEMS since many micromodules with sensors, actuators, and electronic circuits can be made with exactly the same effort it takes to make just one module. Various functions should be realized by using logic circuits or softwares in microprocessors integrated in modules.

Therefore, the key idea of DMMS is to coordinate simple motions of many microactuators in order to perform a practical task. One of the major problems in present microactuators is friction. Friction in micro scale prohibits us from using gears and joints because they waste too much energy. Suspended actuators do not suffer from friction but have limited motion range up to a few tens of micrometers. If many such microactuators are arranged in series and parallel [8]–[10], the overall structure can produce larger force and displacement and perform more complicated functions than each simple actuator. Because these actuators are driven directly, energy loss associated with transmission of motion is minimal. They can even utilize the friction between an object and them to transmit driving force. The control signal may be given to group of actuators; that will eliminate the wiring problem to the system with many active elements.

In order to demonstrate the concept of DMMS, we have proposed a ciliary motion system (CMS) which is one type of the DMMS [1]. The system mimics the motion and function of cilia in living organisms. Many cantilever actuators vibrate in synchronization and convey objects. As elements of the CMS, thermobimorph cantilever actuators made of polyimide were developed and their motion was experimentally confirmed [11]. An object was conveyed by the coodinated motion of the CMS composed of many thermobimorph cantilever actuators. In the future, sensors and controllers will be integrated with actuators because they are necessary to compose a primary servosystem and to reduce the amount of information exchange.

II. Ciliary Motion Systems

Obs rving living organisms, we are often stimulated to have ideas of novel MEMS architectures. One such example is ciliary motion which provides propulsion for or-

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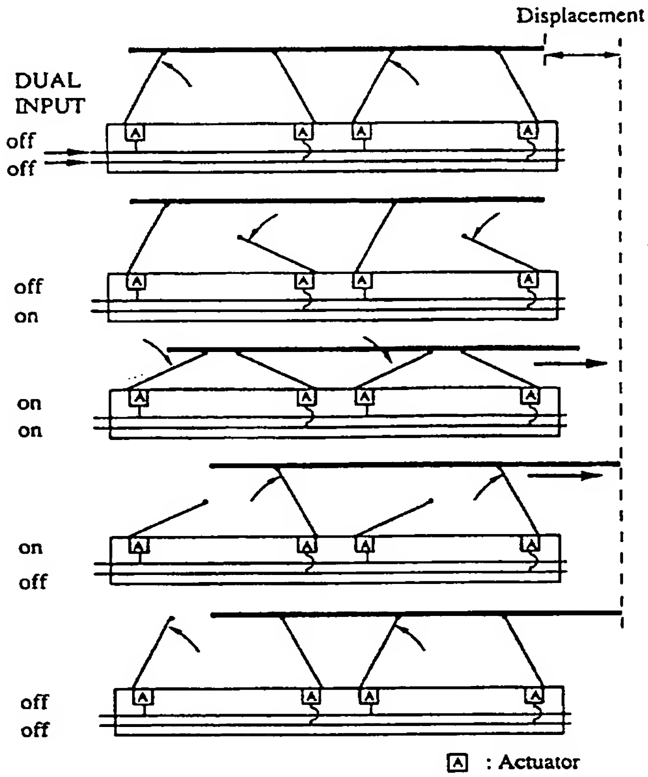

Fig. 1. Driving principle of CMS.

ganisms. The ciliary motion is based on the motion of ciliates, which are microscopic organisms having many hairlike protrusions (cilia) on the surfaces of their cells. They accomplish locomotion by vibrating cilia cooperatively. In the human body, cilia on the epithelial cells lining the respiratory tract sweep layers of mucus together with external particles. This method of locomotion in a ciliate can be adapted in a device to convey objects.

Fig. 1 is the simplest implementation of the ciliary motion system by means of MEMS, which works as a conveyor of a plate. The function of the system is realized by two sets of cantilevers arranged opposing each other. This system has one degree of freedom in conveying the plate and is composed of exactly the same modules. The motions of actuators in the modules are very simple and can be easily realized by thermobimorph cantilever actuators. Similar implementation was proposed by Benecke *et al.* [12] based on silicon and gold composite cantilevers developed by them [13]. The system reported in this paper receives all the control signals from the outside. It is the first step towards the future goal of integrating sensors or electronic circuits into this system.

III. Microactuators for CMS

A. Cantilever Using Polyimides

A thermally driven cantilever actuator, which is developed for CMS, consists of two layers of polyimide which have different thermal expansion coefficients and a metal

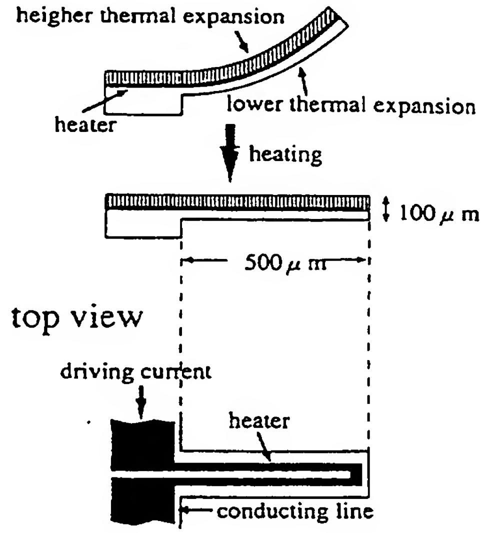

Fig. 2. Thermally driven cantilever actuator made of polyimide. Cross-sectional view.

microheater sandwiched by them [11]. As an initial shape without heating, it curls up above the substrate because of the difference of the residual stress of two polyimide layers, and flattens when it is heated because of the thermal expansion like a bimetal. Fig. 2 shows the principle of actuation.

We used polyimide as the structural material of the cantilever. The fabrication process is much simpler than that for the silicon/gold cantilever by Riethmüller and Benecke [13] because of the following features:

1) Polyimide has much larger thermal expansion coefficient and smaller Young's modulus than metals and silicon. Therefore large displacements can be obtained with small change in temperature.

2) No additional insulation is necessary around the heater because polyimide is an insulator. It results in the reduction of numbers of layers in the cantilevers and process steps.

3) Polyimide films can be easily spin-coated.

Polyimide with a higher thermal expansion coefficient coats in the upper layer, and that with a lower coefficient in the lower layer. In this case, the cantilever after the releasing process curls up from the substrate, because polyimide with the higher thermal expansion coefficient has stronger residual tensile stress after the baking process than the other polyimide in the lower layer. This composition of the cantilevers prevents adhesion between them and the substrate when they are released.

B. Fabrication Sequence

The four masks fabrication process outlined in Fig. 3 is employed. First, the aluminum sacrificial layer [14] of 1.6 μm thickness is coated by vacuum evaporation, and then it is patterned to form the spacer beneath the cantilever and the conducting lines which connect the heaters in parallel (mask 1). Polyimide of lower thermal expan-

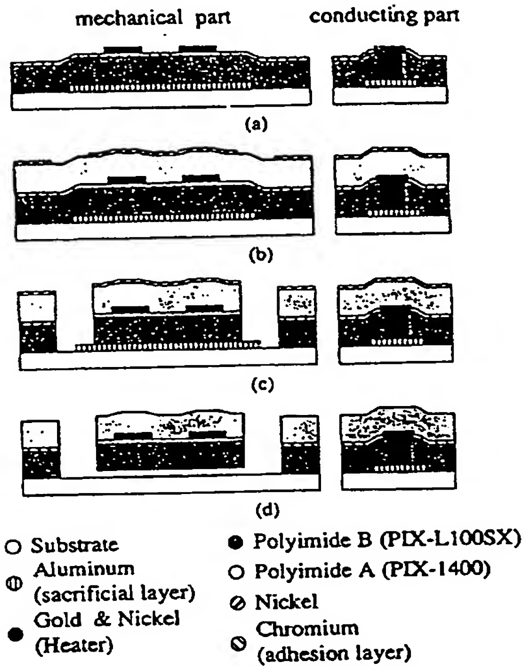

Fig. 3. Fabrication sequence of cantilever actuators. (a) The 1.6-μm-thick Al (sacrificial layer) is patterned. The first 2.2-μm-thick polyimide is coated and patterned. The adhesion layer (Cr) and the metal microheater (Au-Ni) are deposited. The microheater is patterned. (b) The second 3.6-μm thick polyimide is coated, Ni (RIE mask) is patterned. (c) After etching of polyimide by O_2 plasma. (d) Released structures.

sion is spin-coated to form a 2.2-μm-thick film, and the through holes to the conducting lines (mask 2) are made. Metallic microheaters (200-nm-thick gold and 100-nm-thick nickel) are formed by vacuum evaporation and patterned by wet etching (mask 3). Adhesion between gold and polyimide is too weak to endure bonding the wire to a gold pad. We know that an evaporated chromium layer is adequate to improve the adhesion, although it is difficult to pattern the narrow line of the heater by wet etching of chromium. To dissolve this difficulty, we evaporated the chromium of 50 nm in thickness prior to gold and nickel evaporation but left the chromium unpatterned until the RIE etching process of polyimides. The electrical conductivity of the very thin chromium layer could be neglected, even though it was not patterned, while the adhesion was improved dramatically.

On top of them, 3.6-μm-thick polyimide with higher thermal expansion was spin-coated. With a patterned nickel as a mask (mask 4), two polyimide layers and a chromium layer sandwiched by them were etched by oxygen RIE. Finally, cantilevers were released by wet etching of the aluminum sacrificial layer.

C. Driving Characteristics of the Actuator

In this section, we describe the driving characteristics of the thermobimorph cantilever actuator; its dimensions were 500 μm length, 100 μm width, and 6 μm thickness. The vertical initial deflecti n owing to residual stress was

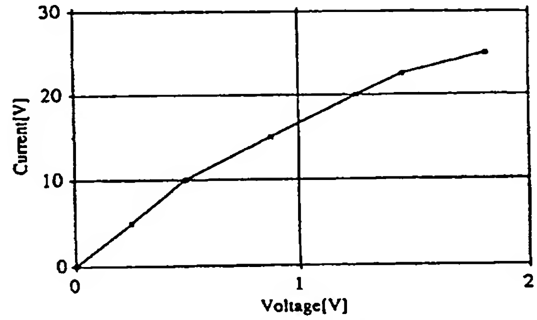

Fig. 4. Current versus voltage relation of the heater.

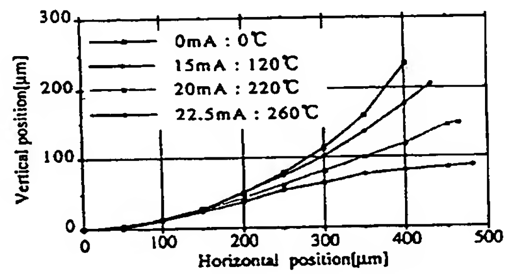

Fig. 5. Change in the shape of the cantilever. Its side views are shown at different current levels.

typically 250 μm above the substrate. The dimensions of the heater line were 20 μm in width, 950 μm in length which included two corners for turning the heater line (see Fig. 2). Numerical analysis showed that heat generation was expected to be the maximum at the corners of the heater.

When the cantilever was heated by flowing current in the heater, it moved downwards and vibrated in the vertical direction with double the frequency of the input sinusoidal current. Resistance of each heater was 30 ~ 50 Ω. Input current up to 25 mA could be supplied without damaging polyimide by overheating.

The following are the results of experiments on driving the thermobimorph cantilever actuator. Fig. 4 shows the voltage-current characteristic. Because of the positive temperature coefficient of resistance, the voltage-current characteristic is not linear. Fig. 5 shows the shape of the cantilever at different current levels. The temperature values given in the same figure were measured by the thermal imager using the infrared ray. In this case, vertical displacement of 150 μm and horizontal displacement of 80 μm were obtained with 22.5-mA drive current in the heater. The current corresponded to the consumed power of 33 mW and the maximum temperature in the cantilever was 260°C. Increasing the input current up to 25 mA, we observed that the temperature ros to 350°C. At this point, the cantilever was severely deformed and its heater was broken. The displacement amplitude at different frequencies f sinusoidal current (14 mA) is shown in Fig. 6. The cut-off frequency (3 dB down) was 10 Hz.

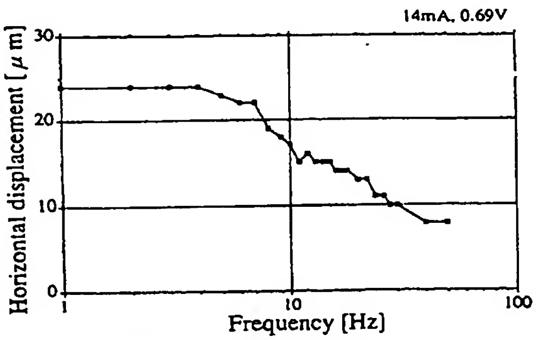

Fig. 6. Frequency dependence of horizontal displacement of the actuator tip.

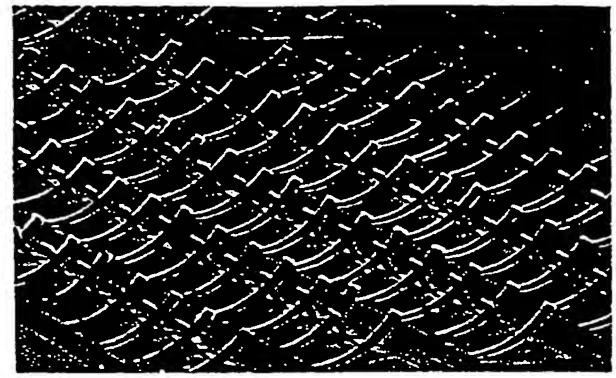

Fig. 7. SEM photograph of CMS.

IV. Motion of CMS

Fig. 7 shows a SEM photograph of CMS which is composed of 512 thermobimorph cantilever actuators on a 1-cm-square substrate. The ciliary motion shown in Fig. 1 was realized by flowing dual square waves which had the delay of quarter wavelength between each other to opposing sets of cantilevers. While the actuators arrayed in the one side of the opposing sets are activated, those in the other side must be bent down and kept away from the object in order not to interfere conveying. Therefore the square wave is suitable for a form of driving current of CMS. The direction of conveyance could be reversed by changing the phase of driving voltages applied to opposing sets of actuators.

We operated one half of the CMS shown in Fig. 7 and observed the conveyance of a load (a silicon piece of 2.6 mm × 1.5 mm × 0.26 mm in size and 2.4 mg in weight). Twenty cantilevers carried the load at the same time. Half the CMS was composed of eight modules connected in parallel, and each module had two sets of 16 opposing cantilever actuators in series. It occupied 1 cm × 0.5 cm in area. The input resistance of the system was 250 Ω. During this experiment, the voltage applied to the system was 16 V and the current was 65 mA; this corresponded to 4-mW power dissipation in each actuator. The experiment was carried out in the ambient air without any cooling equipment.

Based upon the static model of conveyance illustrated in Fig. 1, the velocity v_f of the conveyed object at the frequency f is equal to the displacement of the plate d_f over a unit cycle of actuator motion multiplied by the frequency f. The displacement of the plate d_f is proportional to the displacement of the actuator a_f at the frequency. From Fig. 1, it is possible to assume that the proportional constant k between d_f and a_f is independent of the frequency. Therefore following equations hold:

$$v_f = d_f f = k a_f f$$

$$k = d_{f=1}/a_{f=1}.$$

The suffix $f = 1$ means a particular value tak n at the driving frequency of 1 Hz. Combining these equations,

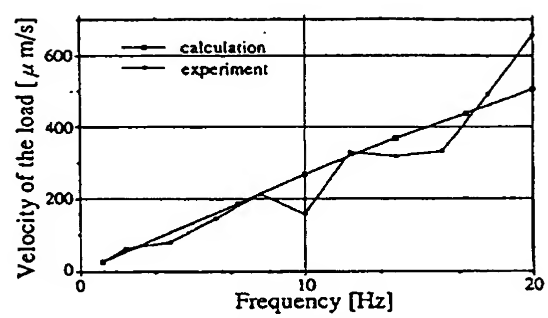

Fig. 8. Dependence of velocity of the load on the driving frequency of CMS. The calculated value is adjusted with 27 μm/s at 1 Hz, which is the experimental value of the velocity at 1 Hz.

one obtains:

$$v_f = d_{f=1}(a_f/a_{f=1})f.$$

Substituting $f = 1$ in this equation, one has $v_{f=1} = d_{f=1}$. Therefore the velocity is given by the following equation:

$$v_f = v_{f=1}(a_f/a_{f=1})f.$$

Please note $a_f/a_{f=1}$ is the frequency response of each cantilever actuator; the measured characteristic for the sinusoidal wave input is given in Fig. 6. The characteristics with the square wave input and the velocity at $f = 1$ Hz were measured. Multiplying them and the frequency f we obtain v_f which is shown as the calculated curve in Fig. 8. In the same figure, we also plot experimental values of the velocity. The velocity of the object at $f = 1$ Hz was 27 μm/s and increased to 650 μm/s at $f = 20$ Hz when the input current of 65 mA was applied to the whole system (or 4 mW to each actuator).

The calculated and measured values agree well. The velocity increased linearly in proportion to the driving frequency up to 10 Hz. The linear relation between the speed and the frequency is expected from the conveyance mechanism shown in Fig. 1 and from the fact that the displacement amplitude of the actuator is constant up to its cut-off frequency. Thus the mechanism of the conveyance is well understood by the static model.

V. Conclusion

One example of DMMS, which is named the ciliary motion system (CMS), is presented. This system is composed of many thermobimorph cantilever actuators arrayed in series and in parallel. Although each actuator has only one-dimensional simple motion with limited displacement, the array of actuators can perform a macroscopic task, conveying objects, by being operated in coordination. In this paper, we reported and demonstrated that CMS could perform its expected function. The conveyance velocity of the object increased linearly to the driving frequency until the speed reached up to 500 μm/s at 10 Hz. The input current of 65 mA at 16 V was supplied to the whole system.

The next step for CMS is to integrate sensors and logic circuits into its modules. By this integration, CMS will be able to control its motion by itself and will become an autonomous distributed system.

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References

[1] N. Takeshima and H. Fujita, "Design and control of systems with microactuator arrays," in *Recent Advances in Motion Control*. K. Ohnishi *et al.* Eds. Nikkan Kogyo Shimbun Ltd., 1990, pp. 125–130.

[2] L.-S. Fan, Y.-C. Tai, and R. S. Muller, "Integrated movable micromechanical structures for sensors and actuators," *IEEE Trans. Electron Dev.*, vol. ED-35, pp. 724–730, 1988.

[3] M. Meheregany, K. J. Gabriel, and W. S. Trimmer, "Integrated fabrication of polysilicon micromechanisms," *IEEE Trans. Electron Dev.*, vol. ED-35, pp. 719–723, 1988.

[4] L.-S. Fan, Y.-C. Tai, and R. S. Muller, "IC-processed electrostatic micromotors," *Sensors and Actuators*, vol. 20, pp. 41–48, 1989.

[5] Y.-C. Tai and R. S. Muller, "IC-processed electrostatic synchronous micromotors," *Sensors and Actuators*, vol. 20, pp. 49–56, 1989.

[6] W. Menz, W. Bacher, M. Hermening, and A. Michel, "The LIGA technique—a novel concept for microstructures and the combination with Si-technologies by injection molding," in *Proc. 4th IEEE Workshop Micro Electro Mechanical Syst.*, Nara, Japan, Jan. 30–Feb. 2, 1991, pp. 69–73.

[7] H. Guckel, K. J. Skrobis, T. R. Christenson, J. Klein, S. Han, B. Choi, and E. G. Lovell, "Fabrications of assembled micromechanical components via deep X-ray lithography," in *Proc. 4th IEEE Workshop Micro Electro Mechanical Syst.*, Nara, Japan, Jan. 30–Feb. 2, 1991, pp. 74–79.

[8] S. M. Bobbio, M. D. Kellam, B. W. Dudley, S. Goodwin-Johnasson, S. K. Jones, J. D. Jacobson, F. M. Tranjan, and T. D. DuBois, "Integrated force arrays," in *Proc. 6th IEEE Workshop Micro Electro Mechanical Syst.*, Fort Lauderdale, FL, Feb. 7–10, 1993, pp. 149–154.

[9] L-Y. Chen, E. J P. Santos, and N. C. MacDonald, "An isolation technology for joined Tungsten MEMS," in *Proc. 6th IEEE Workshop Micro Electro Mechanical Syst.*, Fort Lauderdale, FL, Feb. 7–10, 1993, pp. 189–194.

[10] M. Minami, S. Kawamura, and M. Esashi, "Distributed electrostatic micro actuator (DEMA)," in *Abstr. Late News Papers, 7th Int. Conf. Solid-State Sensors and Actuators*, Yokohama, Japan, June 7–10, 1993, pp. 2–3.

[11] N. Takeshima and H. Fujita, "Polyimide bimorph actuators for a ciliary motion system," in *ASME WAM, Symp. Micromech. Sensors, Actuators Syst.*, DSC-vol. 32, pp. 203–209, 1991.

[12] W. Benecke and W. Riethmüller, "Applications of silicon-microactuators based on bimorph structures," in *Proc. 2nd IEEE Workshop Micro Electro Mechanical Syst.*, Salt Lake City, UT, Feb. 20–22, 1989, pp. 116–120.

[13] W. Riethmüller and W. Benecke, "Thermally excited silicon microactuators," *IEEE Trans. Electron Dev.*, vol. ED-35, pp. 758–763, 1988.

[14] M. Schmidt, R. Howe, S. Senturia, and J. Haritonidis, "Design and calibration of a microfabricated floating-element shear-stress sensor," *IEEE Trans. Electron Dev.*, vol. ED-35, pp. 750–757, 1988.

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